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Searches for Light New Physics at *BABAR*

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Abstract. B-factories are ideal machines to probe for light New Physics, thanks to their high luminosities and low background environments. In the following, we report recent searches for a light Higgs boson, lepton universality violation and dark matter candidates performed with the *BABAR* detector. No evidence for physics beyond the Standard Model is observed and constraints on the existence of these new particles are derived.

Keywords: B-factories, Supersymmetry, light Higgs boson, lepton universality, dark matter

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INTRODUCTION

During the last decade, B-factories have shed some light on many aspects of precision physics, from CP violation to spectroscopy. To broaden its reach for New Physics, *BABAR* [1] recorded additional data samples of 30 fb^{-1} at the $\Upsilon(3S)$ resonance and 14 fb^{-1} at the $\Upsilon(2S)$ resonance, corresponding to $122 \times 10^6 \Upsilon(3S)$ and $99 \times 10^6 \Upsilon(2S)$. In the following, we report searches for a light Higgs boson, lepton universality violation and dark matter candidates in bottomonium decays, as well as dark sector gauge bosons in e^+e^- interactions.

SEARCH FOR LIGHT CP-ODD HIGGS BOSON IN $\Upsilon(2S)$ AND $\Upsilon(3S)$ DECAYS

Several extensions of the Standard Model (SM) predict the existence of a light Higgs boson. For example, the Next-to-Minimal Supersymmetric Standard Model contains a CP-odd Higgs boson (A^0), whose mass need not be larger than $2m_b$ [2]. Its coupling to b -quarks is significant and radiative $\Upsilon(nS)$ ($n = 1, 2, 3$) decays offer an ideal environment to probe for such a possibility. The branching fraction $\Upsilon(nS) \rightarrow \gamma A^0$ is predicted to be up to 10^{-4} , depending on the A^0 mass and couplings, and could be readily detected at B-factories. We report three searches for a light CP-odd Higgs boson in $\Upsilon(2,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$ [3], $\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$ [4] and $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$ decays [5].

The $\Upsilon(2,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$ candidates are reconstructed by combining two oppositely-charged tracks with a photon. At least one track must be identified as a muon and the energy of the photon in the center-of-mass (CM) frame is required to be larger than 0.5 GeV . No additional tracks or photons must be detected in the event. The $\Upsilon(2,3S)$ candidates are then vertexed, constraining their CM energies to the total beam energy, and imposing a common vertex for the decay products. The signal yield is extracted as a function of the A^0 mass by a series of unbinned extended maximum likelihood fits to the distribution of the dimuon mass. The fits are performed in the range $0.212 < m_A < 9.3 \text{ GeV}$ in steps of $2 - 5 \text{ MeVs}$.

The two taus in the $\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$ reaction are reconstructed through their leptonic decays, $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ and $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$. Events containing exactly two oppositely-charged tracks, identified as muons or electrons, and at least one photon with an energy greater than 100 MeV are selected. The background, mainly radiative τ production and two-photon processes, is reduced using a set of eight kinematic and angular variables, optimized in five regions of the photon energy. The signal yield is extracted as a function of the A^0 mass in the interval $4.03 < m_A < 10.1 \text{ GeV}$ by fitting simultaneously the photon energy distribution of the $ee\gamma, \mu\mu\gamma$ and $e\mu\gamma$ samples.

Signal $\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$ events are characterized by a single energetic photon as well as large missing energy and momentum. The $\Upsilon(1S)$ mesons are tagged through the $\Upsilon(2,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ transition. Events containing two tracks, identified as pions, and a single energetic photon are selected. A multivariate classifier based on variables describing the dipion transition is used to improve the purity of the $\Upsilon(1S)$ sample. Additional criteria are further applied to reject background from radiative Bhabha events as well as $\Upsilon(1S) \rightarrow \gamma n\bar{n}$ and $\Upsilon(1S) \rightarrow \gamma K_L^0 K_L^0$ decays. Both resonant two-body decays, $\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$, and non-resonant three-body processes, $\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \chi\bar{\chi}$, are

TABLE 1. Results of light Higgs boson searches performed by the *BABAR* Collaboration.

	Mass range (GeV)	Branching fraction u.l. (90% CL)
$\Upsilon(2,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$	$0.212 < m_A < 9.3$	$(0.26 - 8.3) \times 10^{-6}$ [3]
$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+ \tau^-$	$4.03 < m_A < 10.1$	$(1.5 - 16) \times 10^{-5}$ [4]
$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$	$m_A < 9.2$	$(1.9 - 37) \times 10^{-6}$ [5]
$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \chi \bar{\chi}$	$m_\chi < 4.5$	$(0.5 - 24) \times 10^{-5}$ [5]

considered, where χ denotes a long-lived weakly interacting particle, such as a neutralino or a dark matter candidate. The signal yield is extracted as a function of the A^0 (χ) mass in the interval $0 < m_A < 9.2 \text{ GeV}$ ($0 < m_\chi < 4.5 \text{ GeV}$) by performing a series of unbinned extended maximum likelihood fits to the dipion recoil mass and the missing mass squared distributions.

The distribution of signal yields of each channel is compatible with the null hypothesis. Upper limits (u.l.) on the different branching fractions are set at 90% CL and reported in Table 1. These results significantly constrain light Higgs boson models.

SEARCH FOR DARK MATTER IN INVISIBLE $\Upsilon(1S)$ DECAYS

While the astrophysical evidence for dark matter is now overwhelming, its precise nature remains so far elusive. Observation of SM particles coupling to undetectable final states might shed some light on its properties. In the SM, the branching fraction of the invisible decay $\Upsilon(1S) \rightarrow \nu \bar{\nu}$ is at the level of 1×10^{-5} [6]. Low-mass dark matter candidates coupling weakly to SM particles could enhance this rate by one or two orders of magnitude [7].

A search for invisible $\Upsilon(1S)$ decays has been performed, using a sample of $\Upsilon(1S)$ mesons produced in the transition $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ [8]. Events containing exactly two oppositely-charged tracks originating from the interaction point are first selected. The $\Upsilon(1S)$ mesons are selected with a multivariate classifier using variables describing the dipion transition. In addition to signal events, the final data sample contains a non-resonant component from a pair of low-momentum pions and a peaking background. The latter arise mainly from two-body decays of the $\Upsilon(1S)$ where the decay products escape undetected, and is kinematically indistinguishable from signal events.

The sum of signal and peaking background yields is extracted by a fit to the dipion recoil mass. The peaking component, evaluated from Monte Carlo simulations, is lastly subtracted. Events containing two pions and one or two additional leptons are used to validate the Monte Carlo predictions. The signal yield is found to be $-118 \pm 105 \pm 124$, where the first uncertainty is statistical and the second systematic. No evidence for $\Upsilon(1S) \rightarrow \text{invisible}$ decays is observed and an upper limit on its branching fraction are set at 3.0×10^{-4} with 90% CL. This result improves almost by an order of magnitude the best previous measurement [9].

SEARCH FOR LEPTON UNIVERSALITY VIOLATION IN $\Upsilon(1S)$ DECAYS

The couplings of gauge bosons to leptons are independent of the lepton flavor in the SM. Aside from small lepton-mass effects, the decay width $\Upsilon(1S) \rightarrow l^+ l^-$ should be identical for all leptons. The ratio $R_{l'l'} = \Gamma(\Upsilon(1S) \rightarrow l^+ l^-) / \Gamma(\Upsilon(1S) \rightarrow l'^+ l'^-)$ is therefore expected to be close to unity. In particular, the SM predicts $R_{\tau\mu} \sim 0.992$ [10]. New Physics, such as a light CP-odd Higgs, could break lepton universality and induce significant deviations from these predictions [11]. The effect is often larger if one of the leptons is a tau.

A test of lepton universality violation has been performed by measuring the ratio of decay widths $\Gamma(\Upsilon(1S) \rightarrow \tau^+ \tau^-) / \Gamma(\Upsilon(1S) \rightarrow \mu^+ \mu^-)$ [12]. The $\Upsilon(1S)$ mesons are identified through the transition $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$. Events containing four tracks, two of which must be identified as muons, and no additional activity are selected to form the muon sample. The tau channel is reconstructed through all one-prong decays of the tau, using a multivariate classifier to improve the signal purity.

The ratio $R_{\tau\mu}$ is extracted by a simultaneous extended unbinned maximum likelihood to both final states. A two-dimensional probability density function (PDF) based on the dimuon and dipion recoil masses is used for the muon sample, while the PDF describing the tau dataset is simply based on the dipion recoil mass. The ratio $R_{\tau\mu}$ is found to be $R_{\tau\mu} = 1.005 \pm 0.013(\text{stat}) \pm 0.022(\text{sys})$. The systematic uncertainty includes contribution from selection and

trigger efficiency, particle identification, track reconstruction efficiency as well as modeling of the various PDFs used in the fit. No significant deviation with the SM prediction is observed. This result improves both the statistical and systematic precision with respect to the previous measurement [13].

SEARCH FOR DARK SECTOR GAUGE BOSONS IN e^+e^- INTERACTIONS

Recent results from terrestrial and satellite experiments have motivated a class of dark matter models [14, 15, 16], which introduce a new force embedded in a hidden sector. In this framework, WIMP-like dark matter particles can annihilate into the corresponding gauge boson force carriers, which subsequently decay to SM particles. This new boson is expected to have a mass $\mathcal{O}(\text{MeV} - \text{GeV})$ and is usually referred to as a dark photon. The dark sector couples to the SM via kinetic mixing with the photon and could be readily produced at low-energy colliders. Non-abelian scenarios introduce additional dark gauge bosons, generically denoted W_D , and could accommodate the signal found by the INTEGRAL satellite [17] and the DAMA modulation data [18].

BABAR has performed a search for di-boson production in the four lepton final state, $e^+e^- \rightarrow W_D W_D', W_D^{(\prime)} \rightarrow l^+l^-$ with $l = e, \mu$, assuming both bosons have similar masses [19]. This search is based on 513 fb^{-1} of data collected mainly at the $\Upsilon(4S)$ resonance. Events containing four leptons originating from the interaction point with a total invariant mass greater than 10 GeV are selected. Criteria on the helicity angle of each boson and the dihedral angle between the two bosons are further applied to reduce the background. Events having dileptonic resonances with similar masses are finally retained to form the final sample.

The signal is extracted as a function of the average dileptonic mass using a profile likelihood method [20]. The scan is performed in the range $0.24 - 5.3 \text{ GeV}$ in 10 MeV steps. No significant signal is observed. Limits on the mixing strength between the dark sector and the SM at the level of 10^{-3} have been set at 90% CL. These limits assume that the dark sector coupling constant is $\mathcal{O}(10^{-2})$, and the branching fractions of a dark gauge boson to e^+e^- and $\mu^+\mu^-$ are similar.

CONCLUSION

B-factories have proved to be versatile machines, offering an ideal environment to search for light New Physics with an unprecedented sensitivity over a wide range of processes. Many results have been recently published, and more are to come in the near future, which will shed some light on our understanding of the physics beyond the SM.

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